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Radial frequency diagram (sunflower) for the analysis of diurnal cycle parameters: Solar energy application

Marija Zlata Božnar [a,*], Boštjan Grašič [a], Primož Mlakar [a], Jacyra Soares [b], Amauri Pereira de Oliveira [b], Tássio Santos Costa [b]

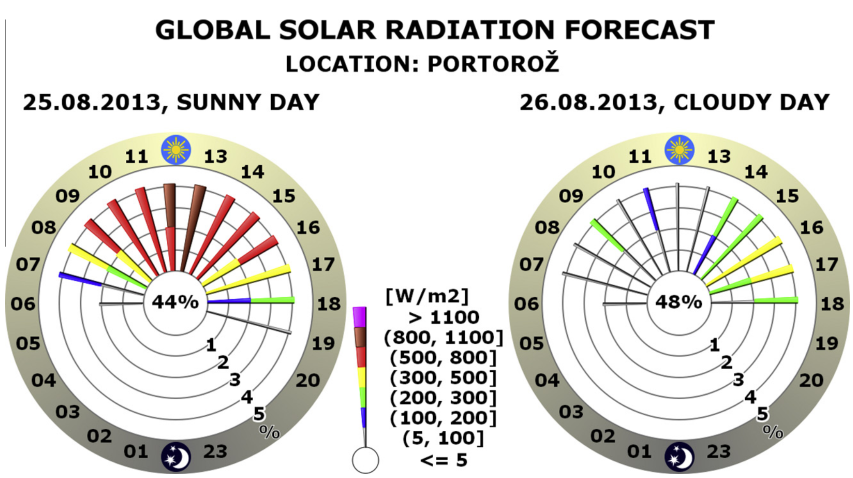
[a] MEIS d.o.o., Mali Vrh pri Šmarju, Slovenia
[b] Group of Micrometeorology, Department of Atmospheric Sciences, University of São Paulo, São Paulo, Brazil

HIGHLIGHTS

- The diurnal cycle of solar energy is important for the management of the electrical grid.
- A solar plant's average production depends on the statistical features of solar radiation.
- The new tool – the "sunflower", is proposed for solar energy availability representation.
- The sunflower identifies and quantifies information with a clear diurnal cycle.
- The sunflower diagram has been developed from the "wind rose" diagram.

GRAPHICAL ABSTRACT

A new type of graphical presentation showing diurnal cycle of solar energy forecast. The application is possible for other parameters related to weather and green energy production.



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ABSTRACT

Many meteorological parameters present a natural diurnal cycle because they are directly or indirectly dependent on sunshine exposure. The solar radiation diurnal pattern is important to energy production, agriculture, prognostic models, health and general climatology. This article aims at introducing a new type of radial frequency diagram – hereafter called sunflower – for the analysis of solar radiation data in connection with energy production and also for climatological studies. The diagram is based on two-dimensional data sorting. Firstly data are sorted into classes representing hours in a day. Then the data in each hourly class is sorted into classes of the observed variable values. The relative frequencies of the value classes are shown as sections on each hour's segment in a radial diagram. The radial diagram forms a unique pattern for each analysed dataset. Therefore it enables the quick detection of features and the comparison of several such patterns belonging to the different datasets being analysed. The sunflower diagram enables a quick and comprehensive understanding of the information about diurnal cycle of the solar radiation data. It enables in a graphical form, quick screening and long-term statistics of huge data quantities when searching for their diurnal features and finding the differences between the data for

* Corresponding author at: MEIS d.o.o., Mali Vrh pri Šmarju 78, SI-1293 Šmarje–Sap, Slovenia.
E-mail address: marija.zlata.boznar@meis.si (M.Z. Božnar).

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several locations. The results of the data analysis using the sunflower diagram show how daily or monthly-based patterns are identified within small or huge data sets. The paper demonstrates the sunflower diagram usefulness over a wide range of applications from green energy production to weather analysis.

1. Introduction

Many physical parameters are directly or indirectly dependent on sunshine exposure, having therefore, a natural diurnal cycle. The amount of sunlight reaching a certain area on the surface of the earth primarily depends on the time and location and secondarily on other atmospheric conditions (cloudiness, fog, particulate matter, photochemical smog, etc.). Time and location dependency can be calculated using a basic trigonometric analysis of the sun's position over the horizon. On the other hand atmospheric conditions form a complex nonlinear filter for sunlight that passes downward and scatters. All together these mechanisms result in complex diurnal cycles.

As a result of the solar diurnal cycle, solar power plants do not generate energy at a constant rate throughout the day, which makes it necessary to eventually purchase additional electricity from conventional sources. Namely, the solar diurnal cycle modulates the electricity price on the market according to the time of the day.

The object of our investigation is the daily pattern of solar energy availability and the seasonal variation of these daily patterns. For that reason, a straightforward representation of the solar diurnal cycle constitutes a useful tool for understanding the production and for planning the acquisition of additional electricity. Also, when deciding on locations for new solar power plants, a clear-cut graphical display of the natural conditions with regard to the availability of solar energy is an important tool for making an effective choice.

The results of the study can contribute to the community interested in solar radiation as an energy source, either directly, through solar collectors or panels, or indirectly, through the production of biomass on land (plants) or in aquatic environments (algae) for subsequent conversion to biofuel. In this context, finding a suitable method for the graphical display of temporal features of solar radiation is a critical issue.

Another question is the form in which solar energy reaches the surface; it is important to know whether the energy reaches the ground directly or as diffuse solar radiation [1,2]. Measurements or reliable weather forecasts can be used to estimate the predominant form of solar energy reaching the ground and this information can then be used to decide which type of solar panel technology should be used [3,4].

The main objective of this work is to introduce a new type of radial frequency diagram (sunflower diagram) for the analysis of solar radiation data in connection with energy production. Renewable energy production systems such as wind mills or photovoltaic plants for electricity production often have a non-uniform energy availability in time. As a consequence of this phenomenon a dedicated sophisticated control of spatial and temporal distributed electricity sources is required. The basic input information for such control is the description of the energy availability patterns. The sunflower diagram is a new possibility to present this description along two dimensions.

The sunflower diagram gives relative frequency information of the mean diurnal variability. The sunflower diagram is a relatively easy way to condense the graphical presentation of the time series with explicit frequency cyclic information. This paper concentrates on sunflower applications showing the diurnal cycle of time series but the new proposed method of graphical presentation is not limited to diurnal cycles. Sunflower presentations can also be generalised to other cycles such as weekly.

There are some other questions in the meteorological analyses that can be answered in a similar way as the question of solar energy availability daily patterns.

Related to climatology, the cloud cover can be displayed in a similar way as the diurnal cycle of global solar radiation. The sunflower representation can also be useful for tourism purposes to display detailed weather information on what a tourist can expect at a given location during the travel period. Another possible application is for traffic or vehicle planning and driver warning or a posteriori traffic analysis. Weather information and traffic analysis examples will be explained in detail in the following sections.

Another interesting potential application is in atmospheric pollution analysis. Not only atmospheric particulate matter and photochemical smog have a decisive effect on horizontal visibility [5] but they also affect the form of how solar energy reaches the surface [6]. Therefore, it is also proposed for the use of sunflower diagrams. Some examples of basic sunflower diagrams are provided in this work.

2. Data and methodology

2.1. Data – the sunflower testbed

The sunflower diagram was applied on a testbed, that contained measurements and model-based forecasts for atmospheric parameters in certain locations in Slovenia and Brazil.

The database contains half-hour average values of measured and predicted atmospheric parameters for the following locations in Slovenia: (i) rural areas over rugged terrain (Maribor, Brnik, Pustice), (ii) rural areas over flat terrain (Rakičan), (iii) coastal areas on rugged terrain (Portorož) and (iv) a town on rugged terrain (Celje). For an urban environment the aforementioned Sao Paulo station was used. The measurement data were provided by the Slovenian Environment Agency (ARSO), Slovenia, MEIS, Slovenia, and IAG, USP, Brazil. The model results were provided by MEIS [7] and created using the *Weather Research and Forecasting Model* (*WRF*) [8,9]. Detailed data about the station's locations and measurements are given in Table 1.

The meteorological stations provided statistically elaborated data every half hour for measurements at ground-level of air temperature, air relative humidity, wind direction and speed, global solar radiation, diffuse solar radiation (only available at some stations) and the Celje station additionally provides PM10, nitrogen oxides and ozone air pollution measurements.

Weather forecasts for complex terrain over Slovenia with fine spatial and temporal resolution (4 km, half-hour) were also prepared for the station locations using the WRF model.

All the results provided in this article are based on the data and tools of the MEIS testbed.

2.2. The phenomenon under investigation

The main question that we want to address with the proposed new analysis technique is the following: We have a time series